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# $e^+e^-$ Annihilations into Quasi-two-body Final States at 10.58 GeV

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We report the first observation of $e^+e^-$ annihilations into hadronic states of positive $C$-parity, $\rho^0\rho^0$ and $\phi\rho^0$. The angular distributions support two-virtual-photon annihilation production. We also report the observations of $e^+e^- \to \phi\eta$ and a preliminary result on $e^+e^- \to \rho^+\rho^-$.

*Keywords*: Exclusive; High momentum; C parity; Helicity amplitude.

## 1. Introduction

The large datasets collected by the $B$ factories provide unique opportunities for studying rare processes and discovering new states. We report several observations of $e^+e^-$ annihilations into quasi-two-body hadronic final states with $C = \pm 1$ at *BABAR* [1–3]. A new avenue for the study of hadron production mechanisms is opened with these observations, and a testing ground for QCD at the amplitude level is provided.

## 2. $e^+e^- \to \rho^0\rho^0, \phi\rho^0$

The process $e^+e^- \to$ hadrons at center-of-mass (c.m.) energy $\sqrt{s}$ far below the $Z^0$ mass is dominated by annihilation via a single virtual photon, thus yielding final state charge-conjugation parity $C = -1$. The Two-Virtual-Photon-Annihilation (TVPA) process, depicted in Fig. 1, with positive final state C parity, has been ignored in incorporating the total hadronic cross section in $e^+e^-$ annihilations into calculations [4] of muon $g$–2, and the running of the QED coupling constant, $\alpha$.

The present analysis uses a 205 fb$^{-1}$ data sample collected at the $\Upsilon(4S)$ resonance, and 20 fb$^{-1}$ collected at c.m. energy 40 MeV lower, using the *BABAR* detector at the SLAC PEP-II asymmetric-energy $e^+e^-$ collider.

The *BABAR* detector is described in detail elsewhere [5].

Events with four well-reconstructed charged tracks and net charge zero are selected. The $\chi^2$ probability of the fitted four track vertex is required to exceed 0.1%, and two oppositely charged tracks must be identified as pions; the other pair must be identified as two pions or two kaons. We accept events with four-particle invariant mass within 170 MeV/c$^2$ of the nominal c.m. energy. Loose signal regions are defined by the mass ranges $0.5 < m_{\pi^+\pi^-} < 1.1$ GeV/c$^2$ and $1.008 < m_{K^+K^-} < 1.035$ GeV/c$^2$. The extracted $\rho^0\rho^0$ and $\phi\rho^0$ yields in these intervals are $1243 \pm 43$ and $147 \pm 13$ events, respectively.

The efficiency-corrected production angular distributions are shown in Fig. 2, where $\theta^*$ is defined as the angle between the $\rho^0_f$ ($\phi$) direction and the $e^-$ beam direction in the c.m. frame. The observed sharply peaking $|\cos\theta^*|$ distributions are consistent with the TVPA expectation [6], which is approximated by:

$$\frac{d\sigma}{d\cos\theta^*} \propto \frac{1+\cos^2\theta^*}{1-\cos^2\theta^*}. \tag{1}$$

For the signal mass regions defined above, and $|\cos\theta^*| < 0.8$, we obtain the following results for the TVPA cross sections near $\sqrt{s} = 10.58$ GeV:

$$\sigma_{\rm fid}(e^+e^- \to \rho^0\rho^0) = 20.7 \pm 0.7(\text{stat}) \pm 2.7(\text{syst})\ \text{fb}$$
$$\sigma_{\rm fid}(e^+e^- \to \phi\rho^0) = 5.7 \pm 0.5(\text{stat}) \pm 0.8(\text{syst})\ \text{fb}.$$

The measured cross sections are in good agreement with the calculations [6, 7]. The Standard Model calculations of the anomalous magnetic moment of the muon and of the QED coupling constant rely on measurements of low-energy $e^+e^-$ hadronic cross sections, which are assumed to be entirely due to single-photon exchange. We have estimated the effect due to the TVPA processes [6] and find it to be small compared with the current precision [4].

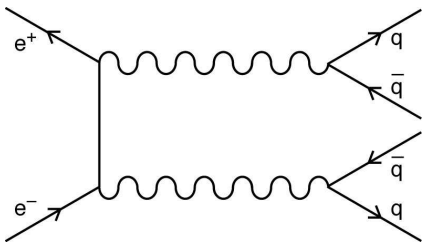


Fig. 1. The two-virtual-photon annihilation diagram.

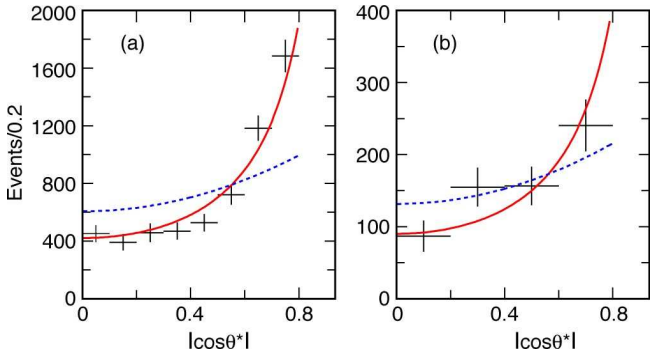


Fig. 2. Production angle distributions, after correction for efficiency, for a) $\rho^0\rho^0$ and b) $\phi\rho^0$. The solid and dashed lines are the normalized $\frac{1+\cos^2\theta^*}{1-\cos^2\theta^*}$ and $1+\cos^2\theta^*$ distributions, respectively.

## 3. $e^+e^- \to \phi\eta$

The process $e^+e^- \to J/\psi\eta_c$ and other double charmonium processes are observed [8] at rates approximately ten times larger than expected from QCD-based models [9]. Various theoretical efforts to understand this have been made recently [10]. An alternate avenue of investigation is provided by the process $e^+e^- \to \phi\eta$, which also involves a vector – pseudoscalar (VP) final state. Different models predict different $s$ dependences for the cross section, and so it is interesting to investigate this by comparing a measurement at $\sqrt{s} = 10.58$ GeV to the CLEO measurement at $\sqrt{s} = 3.67$ GeV [11].

This analysis uses 204 fb$^{-1}$ of $e^+e^-$ colliding beam data collected on the $\Upsilon(4S)$ resonance at $\sqrt{s} = 10.58$ GeV and 20 fb$^{-1}$ collected 40 MeV below. Events with exactly two well-reconstructed, oppositely charged kaon tracks and at least two well-identified photons are selected. We fit the two tracks to a common vertex, and require the $\chi^2$ probability to exceed 0.1%. Each photon candidate is required to have a minimum laboratory energy of 500 MeV. Events with a reconstructed $K^+K^-\gamma\gamma$ invariant mass within 230 MeV/c$^2$ of the $e^+e^-$ c.m. energy are accepted for further study.

We define the $\phi$ mass window as $1.008 < m_{KK} < 1.035$ GeV/c$^2$, and extract $24 \pm 5$ $\phi\eta$ signal events in the $\phi$ mass window, with $\eta \to \gamma\gamma$. The significance is estimated to be 6.5 sigma.

The final radiation-corrected cross section for $1.008 < m_\phi < 1.035$ GeV/c$^2$ within $|\cos\theta^*| < 0.8$ near $\sqrt{s} = 10.58$ GeV is:

$$\sigma_{\rm fid}(e^+e^- \to \phi\eta) = 2.1 \pm 0.4({\rm stat}) \pm 0.1({\rm syst})\ {\rm fb}.$$

The cross section, extended to the full range of $\cos\theta^*$ by assuming a $1 + \cos^2\theta^*$ distribution, is:

$$\sigma(e^+e^- \to \phi\eta) = 2.9 \pm 0.5(\text{stat}) \pm 0.1(\text{syst}) \text{ fb}.$$

There is currently no direct prediction for the cross section of this process at this energy, but the $e^+e^- \to$ VP cross section is expected to have a $1/s^2$ [12] or $1/s^4$ [13,14] dependence in QCD-based models. A comparison between our result and that of CLEO, ($\sigma = 2.1^{+1.9}_{-1.2} \pm 0.2$ pb) at $\sqrt{s} = 3.67$ GeV (continuum) [11], favors a $1/s^3$ dependence (Fig. 3).

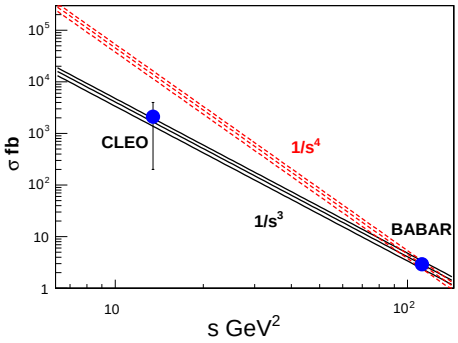


Fig. 3. Cross section extrapolations based on *BABAR*'s measurement at $\sqrt{s} = 10.58$ GeV assuming a $1/s^3$ (black) or $1/s^4$ (red) energy dependence. The bands show one standard deviation uncertainties in the extrapolations. The CLEO measurement at $\sqrt{s} = 3.67$ GeV is also shown.

## 4. $e^+e^- \to \rho^+\rho^-$ (preliminary result)

Since charged $\rho$'s are involved, the $e^+e^- \to \rho^+\rho^-$ process is unlikely to occur through TVPA [1,6,7], unless there is significant final quark recombination between the products of the two virtual photons, or unless there is significant final state interaction ($e^+e^- \to \rho^0\rho^0 \to \rho^+\rho^-$) [15]. Assuming a one-photon production mechanism, this VV ($\rho^+\rho^-$) final state is described by three helicity amplitudes. A study of this reaction can then provide an experimental test of QCD at the amplitude level [14] [13] through investigation of the final states angular correlations.

This analysis uses 343 fb$^{-1}$ of $e^+e^-$ colliding beam data collected on the $\Upsilon(4S)$ resonance at $\sqrt{s} = 10.58$ GeV and 36 fb$^{-1}$ collected 40 MeV lower. Events with exactly two well-reconstructed, oppositely charged tracks identified as pions and at least two well-reconstructed $\pi^0$s are selected. We fit

*BABAR Preliminary*

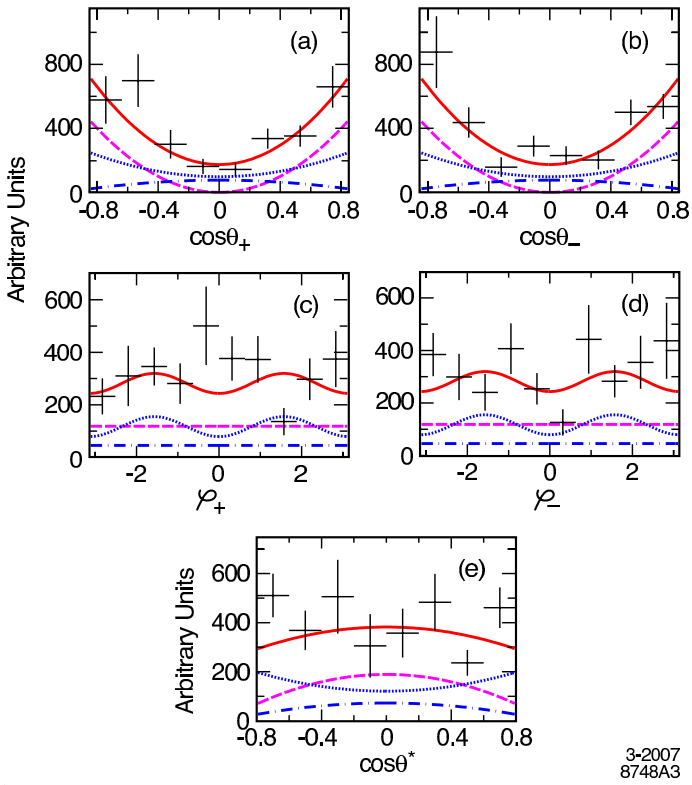


Fig. 4. The s-weighted and efficiency corrected a) $\cos\theta_+$ b) $\cos\theta_-$ c) $\varphi_+$ d) $\varphi_-$ e) $\cos\theta^*$ distributions for $e^+e^- \to \rho^+\rho^-$. The magenta dashed curves show the contributions from $F_{00}$, the blue dotted curves are $F_{10}$, the blue dashed-dotted curves are $F_{11}$, and the solid red curves show the total result.

the charged tracks to a common vertex, and require the $\chi^2$ probability to exceed 0.1%. Each $\pi^0$ is reconstructed through its $\gamma\gamma$ decay channel by requiring the two photon invariant mass to be within the range [0.1,0.16] GeV/c$^2$, and then constraining its mass to the nominal value. We accept events with $|m_{\pi^+\pi^0\pi^-\pi^0} - E_{cm}| < 0.28$ GeV and $|\Delta p| < 0.2$ GeV/c, where $E_{cm}$ is the total c.m. energy, and $\Delta p$ is the momentum difference between the $\pi^+\pi^0\pi^-\pi^0$ system and the $e^+e^-$ system.

We define the $\rho^\pm$ mass intervals as [0.5,1.1] GeV/c$^2$, and extract $308\pm25$ $\rho^+\rho^-$ signal events in the defined mass region. The significance is estimated to be 9.5 sigma.

Assuming $\rho^+\rho^-$ is produced through one photon or $\Upsilon(4S)$, there are three independent helicity amplitudes ($\mathrm{F}_{\mu\nu}$, $\mu/\nu$ is the helicity of $\rho^+/\rho^-$), $\mathrm{F}_{00}$, $\mathrm{F}_{10}$, and $\mathrm{F}_{11}$ ($\mathrm{F}_{10} = \mathrm{F}_{-10} = \mathrm{F}_{0\pm1}$, $\mathrm{F}_{11} = \mathrm{F}_{-1-1}$) [16]. The one-dimensional projections for the decay angles involved can be expressed as:

$$\frac{dN}{d\cos\theta^*} \propto (\sin^2\theta^*|F_{00}|^2 + 2(1+\cos^2\theta^*)|F_{10}|^2 + 2\sin^2\theta^*|F_{11}|^2) \qquad (2)$$

$$\frac{dN}{d\cos\theta_\pm} \propto (\cos^2\theta_\pm|F_{00}|^2 + (1+\cos^2\theta_\pm)|F_{10}|^2 + \sin^2\theta_\pm|F_{11}|^2) \qquad (3)$$

$$\frac{dN}{d\varphi_\pm} \propto (|F_{00}|^2 + (4-\cos 2\varphi_\pm)|F_{10}|^2 + 2|F_{11}|^2) \qquad (4)$$

where $\theta^*$ is the $\rho$ production angle, $\theta_\pm$ ($\varphi_\pm$) is the helicity (azimuthal) angle of the pion from $\rho$ decay. From the two dimensional mass fit ($\pi^+\pi^0$ and $\pi^-\pi^0$), we can calculate a $\rho^+\rho^-$ signal sWeight [17] for each event (including those events outside the defined $\rho^\pm$ mass window) and use it to produce signal angular distributions. We fit the five angular distributions to Equs. 2, 3 and 4 simultaneously by minimizing $\chi^2$. The correlations among the five angles are neglected; this is justified by means of fits to events generated according the assumed PDFs (toy MC). We normalize the amplitudes such that $|F_{00}|^2 + 4|F_{10}|^2 + 2|F_{11}|^2 = 1$ since we have 1 $F_{00}$, 4 $F_{10}$ and 2 $F_{11}$ amplitude contributions. The normalized amplitudes from the fit are found to be in the ratio: $|\mathrm{F}_{00}|^2 : |\mathrm{F}_{10}|^2 : |\mathrm{F}_{11}|^2 = 0.51 \pm 0.14(\mathrm{stat}) \pm 0.02(\mathrm{syst}) : 0.10 \pm 0.04(\mathrm{stat}) \pm 0.01(\mathrm{syst}) : 0.04 \pm 0.03(\mathrm{stat}) \pm 0.00(\mathrm{syst})$, and $|\mathrm{F}_{00}|^2$ deviates from 1 with significance more than 3 sigma. This disagrees with a QCD prediction [14], and suggests that either the decay is not dominated by single-photon exchange as naively expected, or that the QCD prediction does not apply to data in our energy region. The final radiation-corrected cross section for $0.5 < m_{\rho^\pm} < 1.1$ GeV/c$^2$, and within $|\cos\theta^*| < 0.8$, $|\cos\theta_\pm| < 0.85$, at near $\sqrt{s} = 10.58$ GeV (assuming only one-photon production) is:

$$\sigma_{\mathrm{fid}}(e^+e^- \to \rho^+\rho^-) = 8.5 \pm 0.7(\mathrm{stat}) \pm 1.5(\mathrm{syst})\ \mathrm{fb}.$$

We extend the cross section calculation from our acceptance region to the full phase space using the fitted amplitude values, and find $20.0 \pm 1.6(\mathrm{stat}) \pm 3.6(\mathrm{syst}) \pm 1.7(\mathrm{ampl})$ fb; the third uncertainty is due to the amplitude uncertainties.

## 5. Conclusion

We report the first observation of $e^+e^-$ annihilations into hadronic states of positive $C$-parity, $\rho^0\rho^0$ and $\phi\rho^0$. We also report the observation of the process $e^+e^- \to \phi\eta$, and obtain preliminary results on $e^+e^- \to \rho^+\rho^-$. The measured helicity amplitude magnitudes from $e^+e^- \to \rho^+\rho^-$ contradict a QCD prediction at a significance of more than 3 sigma.

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## References

1. B. Aubert *et al.*, Phys. Rev. Lett. **97**, 112002 (2006).
2. B. Aubert *et al.*, Phys. Rev. D (R) **74**, 111103(R) (2006).
3. F. Blanc for *BABAR* Collaboration, Morind QCD 2006.
4. M. Davier, S. Eidelman, A. Hoecker, Z. Zhang, Eur. Phys. Jour. C 31, 503 (2003).
5. B. Aubert *et al.*, Nucl. Instrum. Methods, Sect. A **479**, 1 (2002).
6. M. Davier, M. Peskin, and A. Snyder, hep-ph/0606155.
7. G. T. Bodwin *et al.*, Phys. Rev. D **74**, 074014 (2006).
8. K. Abe *et al.*, Phys. Rev. Lett. **89**, 142001 (2002); B. Aubert *et al.*, Phys. Rev. D **72**, 031101 (2005).
9. E. Braaten and J. Lee, Phys. Rev. D **67**, 054007 (2003), [Erratum-ibid. D **72**, 099901 (2005)]; K. Y. Liu, Z. G. He and K. T. Chao, Phys. Lett. B **557**, 45 (2003).
10. A. E. Bondar and V. L. Chernyak, Phys. Lett. B **612**, 215 (2005); G. T. Bodwin, D. Kang and J. Lee, hep-ph/0603185; Y. Zhang, Y. Gao, and K. T. Chao, Phys. Rev. Lett. **96**, 092001 (2006); G. T. Bodwin, D. Kang, T. Kim, J. Lee, and C. Yu, hep-ph/0611002.
11. G. S. Adams *et al.* (CLEO Collaboration), Phys. Rev. D **73**, 012002 (2006).
12. J. M. Gerard and G. Lopez Castro, Phys. Lett. B **425**, 365 (1998).
13. V. Chernyak, hep-ph/9906387.
14. V. L. Chernyak and A. R. Zhitnitsky, JETP Lett. **25**, 510 (1977); [Pisma Zh. Eksp. Teor. Fiz. **25**, 544 (1977)]; G. P. Lepage and S. J. Brodsky, Phys. Lett. B **87**, 359 (1979); G. P. Lepage and S. J. Brodsky, Phys. Rev. D **22**, 2157 (1980); S. J. Brodsky and G. P. Lepage, Phys. Rev. D **24**, 2848 (1981).
15. M. Gell-Mann, D. Sharp, and W. G. Wagner, Phys. Rev. Lett. **8**, 261 (1962); P. Kroll, hep-ph/0112274.
16. M. Jacob, and G. C. Wick, Ann. Phys.. (N. Y.) **7**, 404 (1959); S. U. Chung, Phys. Rev. D **57**, 431 (1998).
17. M. Pivk and F. R. Le Diberder, Nucl. Instrum. Meth. A **555**, 356 (2005).